Hyperion On-Orbit Validation of Spectral Calibration using Atmospheric Lines and an On-board System

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ABSTRACT

The Hyperion instrument mounted on the EO-1 spacecraft was launched November 21, 2000 into an orbit following LANDSAT-7 by 1 minute. Hyperion has a 7.5 km swath width, a 30 meter ground resolution and 220 spectral bands. Its spectral bands extend from 400 nm to 2500 nm with each band having about a 10 nm bandwidth. A unique process to validate the spectral calibration was developed. The process was based on an atmospheric limb collect and supported with a solar calibration collect. The data contained a collection of solar lines, atmospheric lines and absorption lines from the paint that coats the solar calibration reflectance panel. Correlating the positions of these lines with reference data, the center wavelength of each pixel across the field of view for the VNIR and SWIR spectral regions of the imaging spectrometer has been verified. In this paper we discuss the data collection and the technique applied to the VNIR and SWIR focal plane array.

Keywords: Hyperspectral Imaging, Spectral Calibration, Hyperion, EO-1

1. INTRODUCTION

One of the primary missions for the Hyperion program is to characterize the radiometric performance of the imaging spectrometer on-orbit and compare it against the performance established during pre-flight acceptance tests. One of the key performance parameters is the spectral calibration. The spectral calibration is defined by a center wavelength and bandwidth at full width half maximum of a modeled gaussian spectral response function. The spectral calibration is defined for each spectral channel for each row of pixels along the spatial dimension.

The observational data required to perform this verification must contain clearly defined spectral features that can be identified and traced to a reference spectrum. We attempted to use features in ground scenes but difficulties arose in removing the spectral continuum. The variable spectral reflection of the earth's surface added uncertainty to the process.

A data collection of earth's atmospheric limb provided a more tractable data source. The atmospheric limb is a solar calibration collect scheduled such that the instrument views the sun through different tangent heights of the atmosphere. In order to view the sun, the spacecraft performs a yaw maneuver such that sunlight reflects off the solar calibration panel into the instrument aperture. The result is a collect that is uniform across the field of view and contains spectral features, which can be matched with solar lines, atmospheric lines and absorption lines associated with the paint on the instrument cover.

We developed a process to identify and match the known spectral features with those in the Hyperion spectrum and then derive the corresponding center wavelengths for each pixel on the focal plane. This paper discusses the details of the data collection event, the atmospheric limb's spectrum and the process of performing the spectral calibration. The results for the derivation of the spectral calibration for the VNIR and SWIR focal plane on-orbit is presented along with comparison with the calibration made during ground acceptance tests described previously by Liao[1].

2. DISCUSSION OF DATA COLLECT

2.1 Atmospheric Limb Collect

The Hyperion instrument telescope cover has three normal positions: closed, open and the solar calibration position. When Hyperion views the ground or the moon, the cover is in the open position. When Hyperion views the sun, the cover is in the solar calibration position—which is 37 degrees from the closed position—and the spacecraft must perform a yaw maneuver so that the instrument views the reflection of the sun off the inside of the cover. A diffuse white paint containing distinct spectral lines coats this surface. The atmospheric limb collect is essentially the same as a solar calibration but timed so that the sun is rising through the limb of the earth and the sun's rays pass through the atmosphere before reaching the instrument, (Fig. 1). The orbital motion of EO-1 allows Hyperion to sample different cross-sections of the atmosphere during image acquisition, which for this type of collect lasts 12 seconds. Fig. 2 is an example of the data that the instrument collects during an atmospheric limb collect.

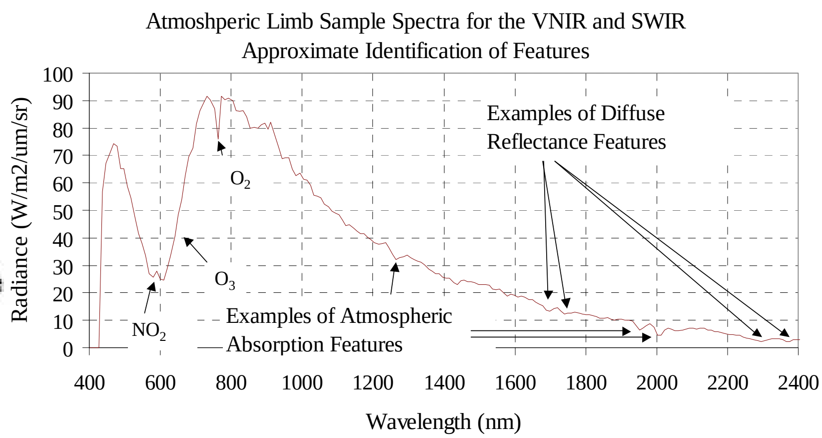

Figure 1: **Schematic of Atmospheric Limb Collect**

Figure 2: **Example of a Spectral Profile obtained during an Atmospheric Limb Collect**

2.2 Reference Spectrum

To perform the spectral validation, the collected limb spectrum must not only have distinguishable features but also be referenced to a known spectrum. Fig. 3 compares the Hyperion spectra with the measured reflectance of the cover paint and the atmospheric lines for the SWIR wavelengths. Correlation points between the Hyperion spectra and features in the cover paint or atmospheric spectra are indicated. The spectrum for the cover paint was obtained by making diffuse reflectance measurements of paint samples with a Cary 5 spectrometer and BioRad Fourier transform spectrometer at TRW. The atmospheric lines in the SWIR were obtained from PLEXUS —a general user interface built for MODTRAN-3, ver. 1.5. The process used for the VNIR and SWIR were slightly different. There were numerous lines that could be used in for the SWIR. Only the oxygen line from the atmospheric limb was used for the VNIR. The remaining features were inconsistent with the atmospheric reference. For the VNIR, a solar line, contained in a solar calibration collect was used in addition to the oxygen line from the atmospheric limb collect.

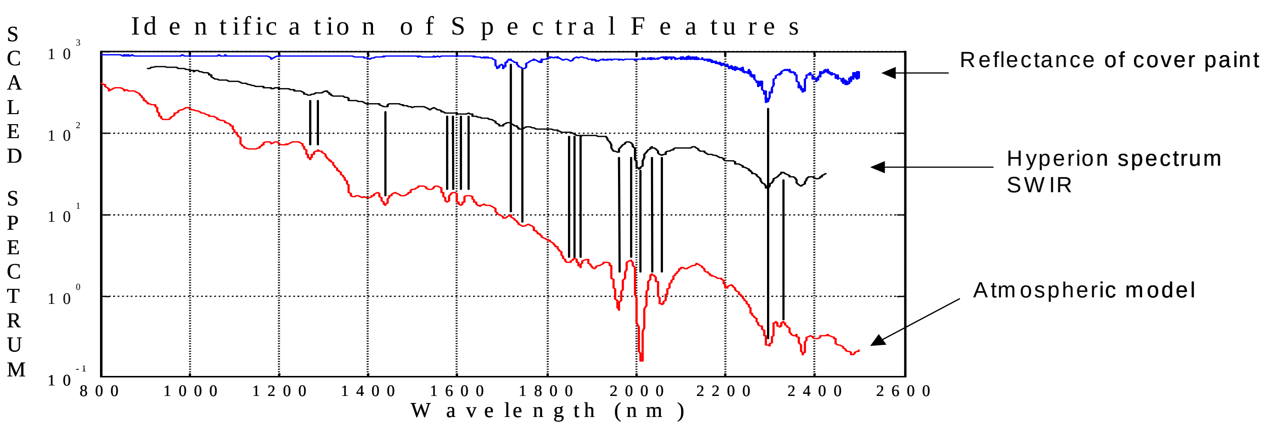

Figure 3: **Hyperion Spectrum in the SWIR (black) with an atmospheric model (red) and reflectance of cover paint (blue).**

3. DATA ANALYSIS

The following steps are the basis for the spectral verification. The steps directly apply to the SWIR spectral verification. The modifications to the process for the VNIR spectral verification are discussed below. We refer to the two axes of the focal plane as 1) the spectral *band*, and 2) the spatial field of view (*FOV*).

1.) *Create Pseudo-Hyperion Spectra from the Reference Data*: The calculated atmospheric limb profile was adjusted to include cover reflectance effects: paint reflectance, BDRF (bi-directional reflection factor), and the spectral angle of reflection. The high-resolution spectrum, sampled at 0.5 nm intervals, was convolved with the instrument's spectral broadening coefficient or qaussian bandwidth. This operation was performed on a pixel-by-pixel basis because the broadening coefficient varied slightly across the focal plane. Finally, the spectrum was fit with a cubic spline to more accurately determine the wavelength positions of peaks and troughs.

2) Correlate Spectral Features: First, a visual comparison was made between the Hyperion and reference spectra in order to identify features of significant strength and spatial presence to be included in the calculations. Nineteen features were identified in the Hyperion atmospheric limb spectrum for the SWIR regime. For each spectral feature—in a given FOV—the location of the peak or trough, in band number units, was determined by applying a cubic spline and calculating the extremum. This was matched with the wavelength of the corresponding feature in the reference spectrum. This process was repeated for each FOV location to take into account the spectral smile. Calculating peak locations using spline interpolation introduced a ±1.1 nm error distribution (determined using empirical sampling of the high-resolution reference spectrum).

3) *Calculate Band-to-Wavelength Map:* The correlation process in step 2 resulted in a 2D surface: the Hyperion band position of a spectral feature (x), the field of view position (y), and the corresponding wavelength of the feature obtained from the reference spectrum (z). We applied a low order polynomial fit to statistically reduce noise in the data and produce a band-to-wavelength map for the focal plane.

The last part of step three was modified for the VNIR. The VNIR spectral verification was based on two lines, a solar line (520 nm) from a solar calibration collect and the oxygen (762.5 nm) from an atmospheric limb collect. Since there were only two points, a complete spectral fit was not possible. Instead the pre-flight spectral calibration table was adjusted by an offset and a tilt to match the solar and oxygen reference lines.

4. RESULTS

3.1 Point-wise Comparison with Pre-Flight Measurements

Pre-flight measurements using a monochrometer were made at distinct wavelengths, 20 locations in the VNIR and 25 locations in the SWIR which spanned each focal plane in the spatial and spectral dimensions. The monochrometer was stepped in wavelength to determine the center wavelength and full-width-half maximum for each of these locations. For the SWIR, there were four spectral features in the atmospheric limb reference spectra that were close in wavelength to these pre-flight measurements. These wavelengths and those corresponding to the spectral band number are compared in Table-1. The most significant difference occurs in a region where there are multiple lines in the atmosphere. We have reservations about the wavelength accuracy of the calculated features in the vicinity 2000 ± 15 nm (having found suspected errors in the VNIR regime, perhaps related to inaccurate model parameters). The results based on the cover lines are in much better agreement with the ground calibration. The accuracy of the technique is limited to the accuracy of the reference spectra. The next largest source of error is due to the use of the spline in determining the peak and trough positions (±1.1 nm). Overall, this comparison indicates that the on-orbit measurements support the ground calibration to within half a pixel. Each pixel has about a 10 nm bandwidth.

TABLE I
SWIR COMPARISON OF ON-ORBIT AND GROUND RESULTS

Spectral Pixel Band	TRW [nm]	On-Orbit [nm]	Delta [nm]	Reference
87	1013.00	--	--	--
147	1315.12	1315.4	+0.28	Atm.
156	1711.55	1710.5	-1.05	Cover
186	2012.19	2015.5	+3.31	Atm.
216	2313.97	2315.4	+1.43	Cover

The results for the VNIR are presented in table II. Band 17 is closest to the solar line used as a reference and band 41 is closest to the oxygen line that was used as a reference. Table II indicates that the on-orbit measurements for the VNIR support the ground calibration to better than half a pixel.

TABLE II
VNIR COMPARISON OF ON-ORBIT AND GROUND RESULTS

Spectral Pixel Band	**TRW [nm]**	**On-Orbit [nm]**	**Delta [nm]**
13	478.31	478.52	+0.20
31	661.36	661.96	+0.60
40	752.89	753.69	+0.80
48	834.24	835.22	+0.98
57	925.77	926.95	+1.18

3.2 Spatial Comparison with Pre-Flight Measurements

The pre-flight calibration was extended to the entire focal plane by applying a polynomial fit to the pre-flight monochrometer data points referred to in the section above. The resulting full calibration consisted of a center wavelength value for each pixel. We applied the same polynomial fit process to the results for the SWIR. The following two figures compare the results from the pre-flight spectral calibration and the on-orbit calibration. Also indicated are the discrete monochrometer based results. Note that for Band 87, Fig. 4, the center wavelength as well as the variation of the center wavelength across the field of view is in excellent agreement with the preflight calibration. The error bars of ± 1nm represent the expected accuracy for this wavelength with the knowledge of the reference spectrum of the diffuse reflectance being < 1nm and the accuracy of the alignment technique being ~ 1nm. For Band 216, Fig. 5, the on-orbit spectral calibration has about a 1.5 nm offset, and the center wavelength variation across the field of view has the same trend as the ground spectral calibration. For this wavelength the error bar is larger due to the larger uncertainty of the reference spectrum.

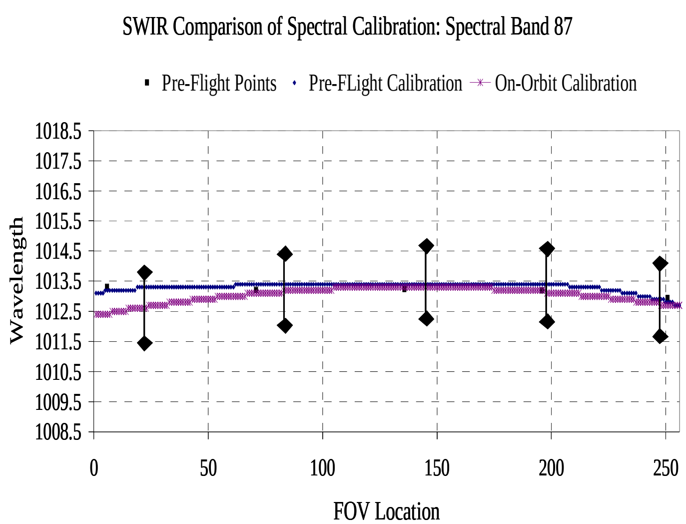

Figure 4: **SWIR Comparison Band 87**

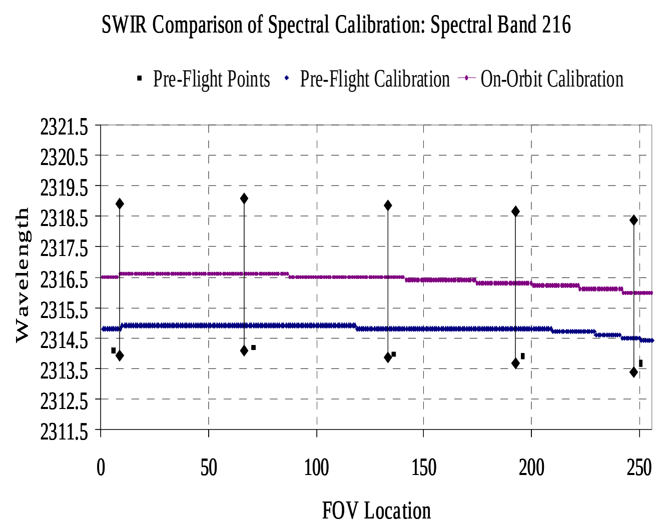

Figure 5: **SWIR Comparison Band 216**

Figures 6 and 7 compare the pre-flight spectral calibration with the on-orbit results for the VNIR. The accuracy of the reference spectrum for the solar line and oxygen line used for the VNIR are expected to be better than 1 nm. The error bars are plotted with an estimated uncertainty of ± 1nm. Both plots suggest a slight rotation between the pre-flight and on-orbit spatial variation. However, recall that for the VNIR that since only two references lines were available, on offset and tilt was applied to the pre-flight calibration to match the solar and oxygen reference lines to create the VNIR on-orbit verification calibration. The apparent rotation could be a bi-product of the data processing method. An additional atmospheric limb has been collected and will be processed with a more current version of atmospheric models in an effort to improve the atmospheric reference for the VNIR.

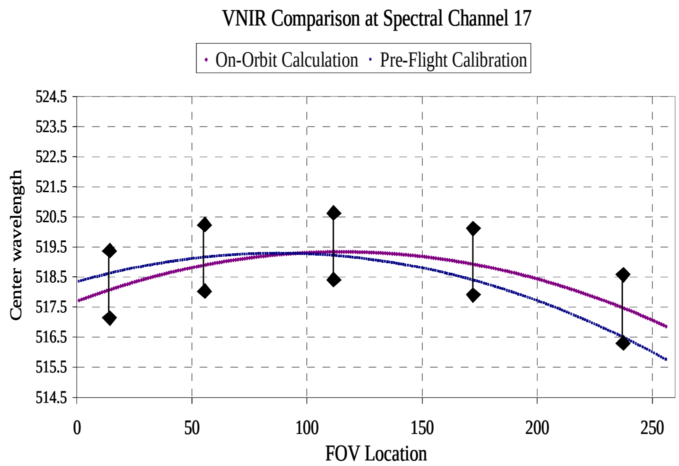

Figure 4: **VNIR Comparison Band 17**

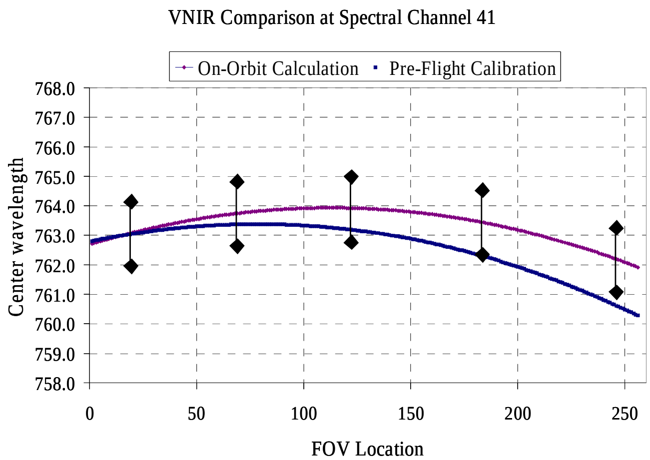

Figure 5: **VNIR Comparison Band 41**

5. CONCLUSIONS

The Hyperion instrument mounted on the EO-1 spacecraft has been successfully performing since it was launched November 21, 2000. One of the primary missions for the Hyperion program is to characterize the radiometric performance of the imaging spectrometer on-orbit and compare it against the performance established during pre-flight acceptance tests. One of the key performance parameters is the spectral calibration. A process to verify the spectral calibration on-orbit was developed.

The on-orbit spectral verification process was based on an atmospheric limb data collect in which the spectral signature is a result of the rays of the sun passing through the atmosphere and reflecting off the Hyperion cover. The results confirm that the Hyperion pre-flight spectral calibration derived on the ground is valid for on-orbit operations. The largest sources of uncertainty in the process are suspected errors in the calculated atmospheric profile. The more precise spectral calibration that was derived pre-flight was released for on-orbit operations. Although periodic repeats of the atmospheric limb collect are planned, the Hyperion spectral calibration is expected to be constant since the Hyperion instrument spectrometer is temperature controlled.

REFERENCES

1. L. Liao, P. Jarecke, D. Gleichauf and T.Hedman, "Performance Characterization of the Hyperion Imaging Spectrometer Instrument", *Proc. of SPIE*, Vol. 4135, pp. 254-263, August 2000.